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Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues

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ABSTRACT

A small scale fixed bed downdraft gasifier system to be fed with agricultural and forestry residues has been designed and constructed. The downdraft gasifier has four consecutive reaction zones from the top to the bottom, namely drying, pyrolysis, oxidation and reduction zones. Both the biomass fuel and the gases move in the same direction. A throat has been incorporated into the design to achieve gasification with lower tar production. The experimental system consists of the downdraft gasifier and the gas cleaning unit made up by a cyclone, a scrubber and a filter box. A pilot burner is utilized for initial ignition of the biomass fuel. The product gases are combusted in the flare built up as part of the gasification system. The gasification medium is air. The air to fuel ratio is adjusted to produce a gas with acceptably high heating value and low pollutants. Within this frame, different types of biomass, namely wood chips, barks, olive pomace and hazelnut shells are to be processed. The developed downdraft gasifier appears to handle the investigated biomass sources in a technically and environmentally feasible manner. This paper summarizes selected design related issues along with the results obtained with wood chips and hazelnut shells.

1. Introduction

Conventional energy production relies heavily on fossil fuels. Therefore the rapid expansion of energy production has brought with it several environmental issues. Fossil fuel resources are declining rapidly. Within this frame, biomass offers an alternative energy source to conventional energy. It already accounts for 5% of the European Union's (EU) energy supply, and 65% of the total renewable energy production [1,2]. The share of biomass in the primary energy consumption is expected to increase globally in the future [3–5].

Thermolysis processes such as combustion, gasification and pyrolysis constitute the major biomass utilization options for primary and secondary energy production. Among these biomass gasification is described as the decomposition of the large polymeric molecules into lighter molecules and eventually to permanent gases (CO, H_2, CH_4, CO_2 and lighter hydrocarbons), ash, char, tar and minor contaminants in the presence of a gasification agent (air, steam, nitrogen, carbon dioxide, oxygen or a combination of these) at elevated temperatures (from 600 °C to above 1000 °C) [6–9].

The following major reactions occur during gasification:

combustion reactions

$$C + 1/2\,O_2 \rightarrow CO \quad -111\ \mathrm{MJ/kmol} \tag{1}$$

$$CO + 1/2\,O_2 \rightarrow CO_2 \quad -283\ \mathrm{MJ/kmol} \tag{2}$$

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$$H_2 + 1/2\,O_2 \rightarrow H_2O \quad -242\ \mathrm{MJ/kmol} \tag{3}$$

the Boudouard reaction;

$$C + CO_2 \rightleftarrows 2CO \quad +172\ \mathrm{MJ/kmol} \tag{4}$$

the water gas reaction;

$$C + H_2O \rightleftarrows CO + H_2 \quad +131\ \mathrm{MJ/kmol} \tag{5}$$

the methanation reaction.

$$C + 2H_2 \rightleftarrows CH_4 \quad -75\mathrm{MJ/kmol} \tag{6}$$

Gasification is based primarily on endothermic reactions. The required process heat is supplied to the gasifier either directly or indirectly. Gasifiers are classified as fixed bed, fluidized bed and entrained flow gasifiers. The latter two are primarily utilized for high calorific value gas production from coal and biomass at high throughputs [9–13]. Fixed bed gasifiers, on the other hand, constitute a practical option for biomass gasification for use in smaller-scale thermal and/or electrical energy generation schemes [9–13]. Fixed bed gasifiers are primarily designed as updraft (countercurrent) and downdraft (cocurrent) reactors.

In the updraft gasifier, the feed is introduced from the top and moves downwards while the gasification agent (air, steam, etc.) is introduced at the bottom so that the product gas moves upwards. The bottom of the bed where the combustion takes place is the hottest part of the gasifier and the product gas exits from the top at lower temperature. The product gas contains large amounts of tar [9–13].

The product gas of the downdraft gasifier contains less tar than that of the updraft gasifier. Biomass fuel is fed at the top; the gasification agent is fed to the combustion zone either from the top or from the sides. Both the fuels and gases move downward and the product gas exits from the bottom at a relatively high temperature. Drying, pyrolysis, combustion and reduction constitute the major reaction zones of a downdraft gasifier from the top to the bottom. The biomass fuel looses moisture in the drying zone. Decomposition of dried biomass into low to high molecular weight volatiles including tar and a carbon rich char occurs in the pyrolysis zone in an almost inert atmosphere. Pyrolytic reactions are in general endothermic. The products of the pyrolysis reactions are partially oxidized in the following combustion zone. Combustion reactions are exothermic. The reduction zone increases the combustible components of the final gas product while decreasing the tar content [2,7–12]. The extent of combustion, gasification, pyrolysis and tar formation/cracking reactions depends on the gasifier design, operation conditions and fuel properties. A throat can be incorporated into the downdraft gasifier design to achieve a low tar content (15–50 mg/Nm^3) product gas. Throated downdraft gasifiers, on the other hand, are less suitable to handle biomass with considerably high ash and moisture contents, namely above about 5% and 25%, respectively [9–13]. Moreover the biomass fuel has to be uniformly sized in the range of 4–10 cm to realise regular flow, no blocking in the throat providing enough room for the pyrolysis gases to flow downwards and to allow heat transport from the throat zone upwards [9–13]. In practice, a tar-free gas is never achieved. Shorter residence times in the hot combustion zone and/or bridging and channelling problems increase the final tar content.

The choice of the fixed bed gasification system is affected by the physical and chemical characteristics of the biomass, the desired capacity of the gasifier and its intended end use application. The updraft gasifier is primarily suitable for thermal applications while the downdraft gasifier is suitable for both thermal and engine applications. Downdraft gasifiers are used in power production applications in a range from 80 up to 500 kWe or more [9–13]. Recently, several fixed bed downdraft gasifier results for hazelnut shells and forestry woods have been published [14–20].

This paper presents selected design and operation related issues of a bench scale throated small scale fixed bed downdraft gasifier system of approximately 10 kg biomass fuel capacity. Results with wood chips and hazelnut shells are presented [20].

2. Materials and methods

2.1. *Characterisation of fuels*

In the experiments, wood chips and hazelnut shells are used as the biomass resource. The wood chips used in this study are obtained from the Kastamonu Integrated Company. The size of wood chips is in the range of 10–30 mm. The hazelnut shells are obtained from the Black Sea region. They are cracked by the supplier to sizes between 5 and 10 mm.

Wood chips and hazelnut shells are grinded to 250 μm size for fuel characterisation analyses. The proximate analysis is determined according to ASTM D 5142-04 standard test method by using LECO TGA701 Termogravimetric Analyzer. The ultimate analysis is determined by using LECO Truspec CHN–S elementary analyzer. C (carbon), H (hydrogen), N (nitrogen) contents of fuels were determined according to ASTM D 5373-02 standard test method. Sulphur (S) contents are determined according to ASTM D 4239-05 test method. Calorific values of fuels are determined by LECO AC350 bomb calorimeter according to ISO 1928:1995 standard test method.

2.2. *Experimental set-up*

The experimental set-up consists of a downdraft gasifier, an ignition unit, a cyclone, a gas cleaning system, a flare and measurement/control and data recording units. Gas which is produced by the gasifier enters the cyclone and then it is divided into two streams. One of the gas streams is directed to the flare while the other one enters the on-line gas analyzer having passed the gas cleaning system [20] (Fig. 1).

2.2.1. *Downdraft gasifier*

A bench scale throated fixed bed downdraft gasifier about 10 kg feeding capacity to be fed with agricultural and forestry residues has been designed and constructed (Fig. 2). The downdraft gasifier has four consecutive reaction zones for drying, pyrolysis, oxidation and reduction from the top to the bottom. Both the biomass fuel and the gases move in the same direction. A throat has been incorporated into the design to achieve gasification with lower tar production. A pilot burner is utilized for initial ignition of the biomass fuel. Air is used as

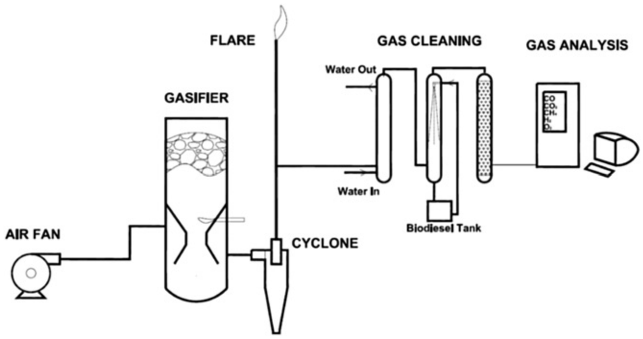

Fig. 1 – Experimental set-up.

the gasification agent. The air blower has a 0.25 kW electrical motor and it can generate 120 m^3/h maximum air flow rate. The air flow rate is controlled by changing the motor speed. An orifice meter calibrated with a Pitot tube is used for measuring the flow rate of the air. Part of the product gases is combusted in the flare built up as part of the gasification system. The gasifier is made of 3 mm thick AISI 310S quality stainless steel. The diameter of the gasifier is 300 mm while the throat diameter is 100 mm (Fig. 2). The total gasifier height is 1095 mm and the throat height is 200 mm. In order to prevent the leakage, the lid located at the top of the gasifier is connected with 8 hinges around the gasifier. The gasifier can be dismantled into two pieces with a flange placed in the middle section. The design allows to gradually preheat the air fed at ambient conditions while flowing through the air jacket into the gasifier combustion zone through 3 air nozzles (10-mm in diameter) spread circumferentially around the cone structure 50-mm above the throat. The ignition port of the gasifier and the air nozzles are located at the same level. The gasification

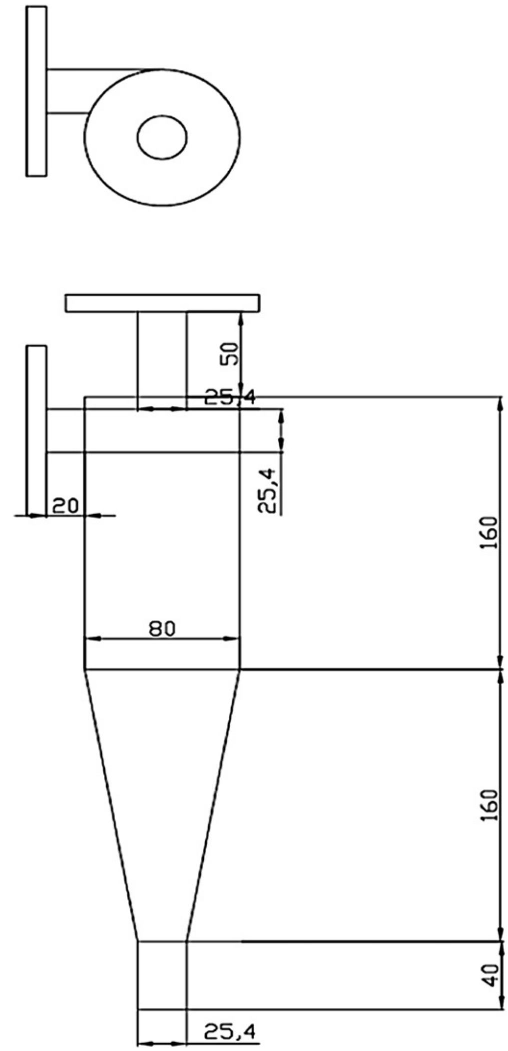

Fig. 3 – Cyclone design.

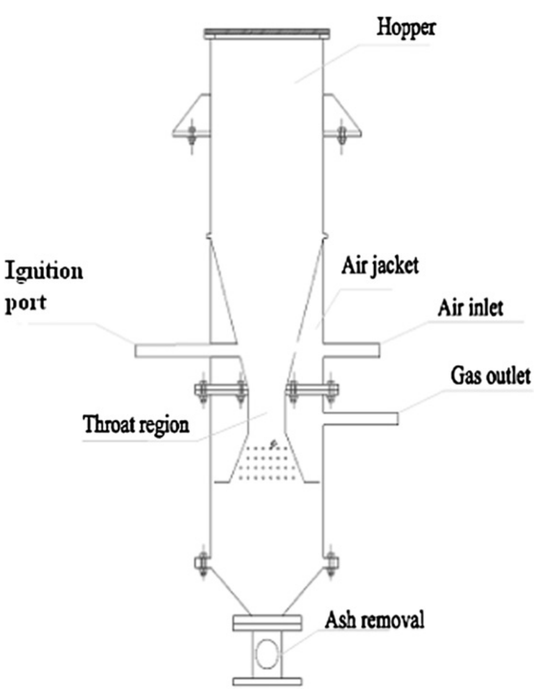

Fig. 2 – Fixed bed downdraft gasifier.

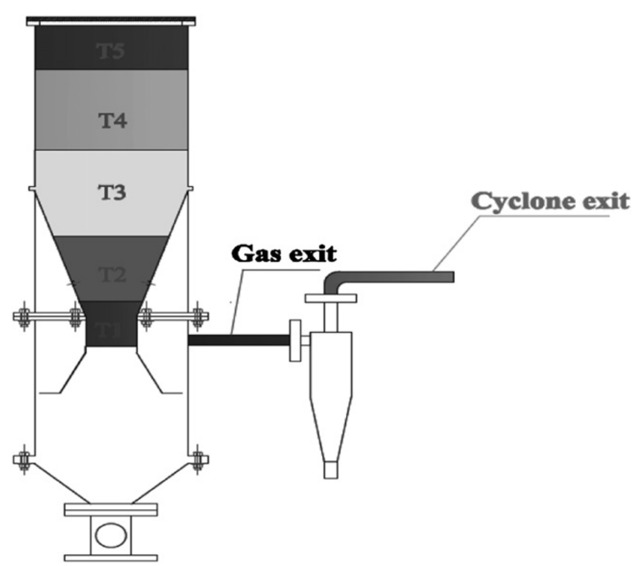

Fig. 4 – Thermocouples on the fixed bed gasifier.

Table 1 – Fuel properties.[a]

Proximate analysis	Units	Wood chips	Hazelnut shells
Volatile matter (VM)	%	77.5	68.2
Fixed carbon (FC)	%	12.3	18.2
Ash (A)	%	1.5	1.1
Moisture content (MC)	%	8.8	12.4
Higher heating value (HHV)	MJ/kg	20.5	19.5
Lower heating value (LHV)	MJ/kg	19.1	17.4
Ultimate analysis	**Units**	**Wood chips**	**Hazelnut shells**
Carbon	%	45.6	45.9
Hydrogen	%	5.9	5.7
Oxygen	%	48.4	48.2
Nitrogen	%	≤1	≤1
Sulphur	%	0.0762	0.0721

a Proximate and ultimate analyses are on as fed and dry bases, respectively.

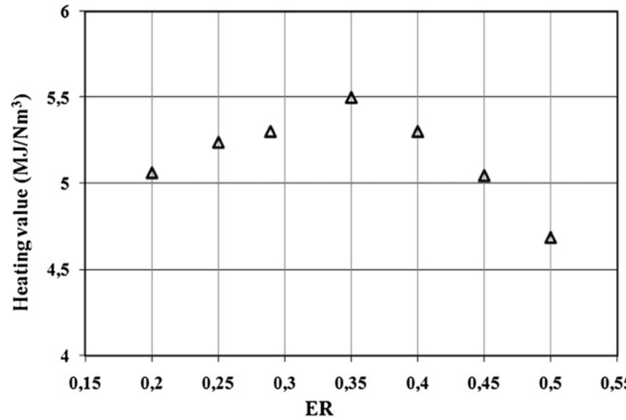

Fig. 6 – Highest lower heating values obtained with wood chips gasification at selected ER.

products passing the throat area are subject to temperatures above 900 °C to achieve low tar content product gas. Gases with finer particulates fill up the outer cone before leaving the gasifier. The air and product gas are separated from each other by a flange (Fig. 2). The gas and air jackets prevent excessive heat loss from the gasifier to remove char and ash after the experiments. Bigger solid particles move to the bottom of the gasifier. A globe valve with 80 mm diameter mounted to the bottom with a flange is used for solids collection.

2.2.2. *Ignition system*

The ignition system has an LPG cylinder and an ionization pilot burner with a capacity of 2.5 kW. The burner head is made of ceramic material. The system is such that it is possible to optimize the length of the flame at the back outlet.

2.2.3. *Cyclone*

A cyclone made of 3 mm thick AISI 310S quality stainless steel is used to remove the particulates in the gas stream. The cyclone design is based on the Lapple model considering high temperature gas cleaning needs. The nominal design assumes an inlet producer gas temperature of 500 °C and a gas flow rate of 25 Nm^3/h. Detailed dimensions of the cyclone are presented in Fig. 3.

2.2.4. *Insulation*

Gasifier, cyclone and all pipes in the system are covered by a 70 mm thick glass fiber to prevent heat loss.

2.2.5. *Gas cleaning system*

The gas cleaning system (Fig. 1) consists of a cooler, a scrubber column and a filter bed. All of them are of cylindrical shape with 100 mm inner diameter. The cooler column is used to cool the gas with water in countercurrent flow. The cooled gas is brought in direct contact with biodiesel in the scrubber to remove the tar components of the gas stream. The perlite-bed column is used to adsorb the remaining tar and moisture of the product gas and to filter fine particulates.

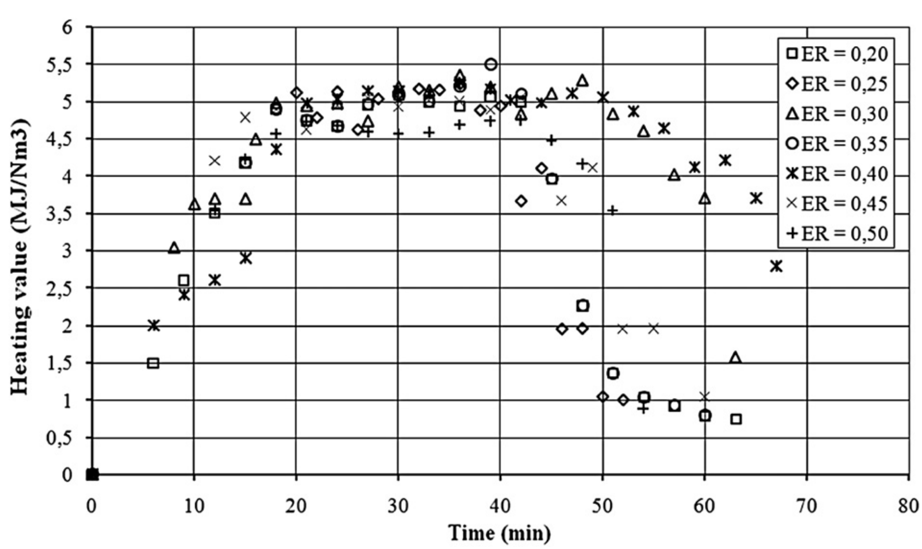

Fig. 5 – Lower heating values for wood chips gasification at selected ER.

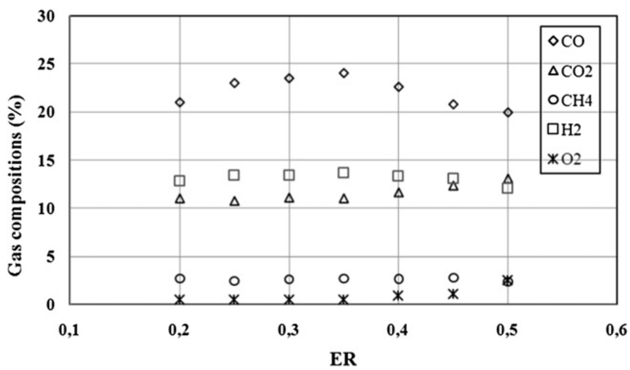

Fig. 7 – Gas compositions obtained with wood chips gasification at selected ER.

2.2.6. *Measurement systems*

Five thermocouples (T1–T5) are used to measure temperature distributions along the fixed bed gasifier throughout each experiment (Fig. 4). T5 and T4 measure the temperature of the drying zone, T3 measures the temperature of the pyrolysis zone, T2 measures the temperature of the oxidation zone and T1 measures the temperature of the reduction zone. Two additional thermocouples are used to measure the temperature of the gasifier and cyclone exits. An analog digital converter is used to record all temperature data every 3 min. The composition of the product gas is measured with ABB AO2000 on-line gas analyzer. CO, CO_2, CH_4 are measured by an infrared analyzer module. H_2 is measured by a thermal conductivity analyzer module. O_2 is measured by a paramagnetic on-line analyzer module. The system has its own gas cooling and filters. The gas is cooled up to 5 °C before measurements. The heating value of the product gas is calculated utilizing the measured concentration of the combustible (CO, CH_4, H_2) components on dry basis. Temperatures and the on-line gas analyzer results are recorded every 3 min during the experiment.

2.3. *Experimental procedure*

Two types of biomass, namely wood chips and hazelnut shells have been processed in the developed downdraft gasifier. In each experiment, the top lid of the downdraft gasifier (Fig. 2) is opened and weighed biomass (about 10 kg) is filled into the gasifier. Then the top lid is closed. Prior to each run, the gasifier is leak checked. Approximately 30 min before starting experiments, the on-line gas analyzer and the gas cleaning system are switched on. Then the air blower is turned on and the air flow rate is first adjusted until the desired combustion level is reached. Then the biomass fuel is ignited and ignition is stopped when the gasifier itself can produce enough heat via combustion to sustain gasification. In general, when the temperature of the T2 (oxidation zone temperature) reaches 600–700 °C, the ignition system is shut down and the ignition port is closed with a blind flange. Runs at different equivalence ratios (ER = 0.2–0.5) are carried out with each biomass to examine the effect of ER on the gas composition and its lower heating value. ER affects the final gas composition and is defined as the actual air to fuel ratio divided by the air to fuel ratio calculated for complete combustion under stoichiometric conditions. The air flow rate associated with the selected ER is determined with respect to the ultimate analysis of biomass The ER is adjusted to produce a gas with acceptably high heating value and low pollutants. Depending on the ER, the temperature gradually increases to about 1000–1200 °C, and CO and H_2 concentrations remain stable around this temperature levels for 20–30 min. Then the temperature gradually decreases along with the gas heating value. When the temperature of T2 reaches 300 °C, the air blower, the gas analyzer and the gas cleaning system are shut down. At the end of each experiment, the globe valve at the bottom of the gasifier is opened to carefully remove the remaining char, ash and unburned biomass. The cyclone is also opened and ash and other particulates are removed before starting a new experiment.

3. Results and discussion

Proximate and ultimate analysis results and heating values of wood chips and hazelnut shells are given in Table 1. The major difference is observed in the proximate analysis results; hazelnut shells have about 55% more fixed carbon than wood chips on dry basis while the wood chips have slightly higher volatile matter content. Wood chips have a slightly higher heating value than hazelnut shells.

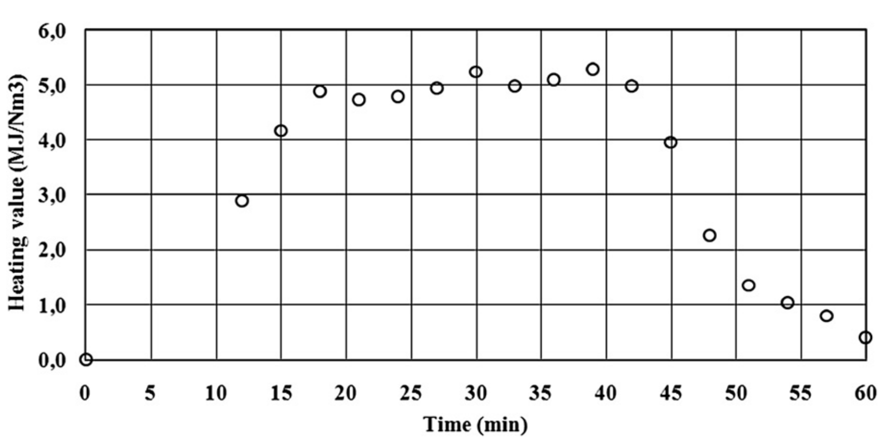

Fig. 8 – Heating values of wood chips experiments at ER = 0.35 during a batch operation.

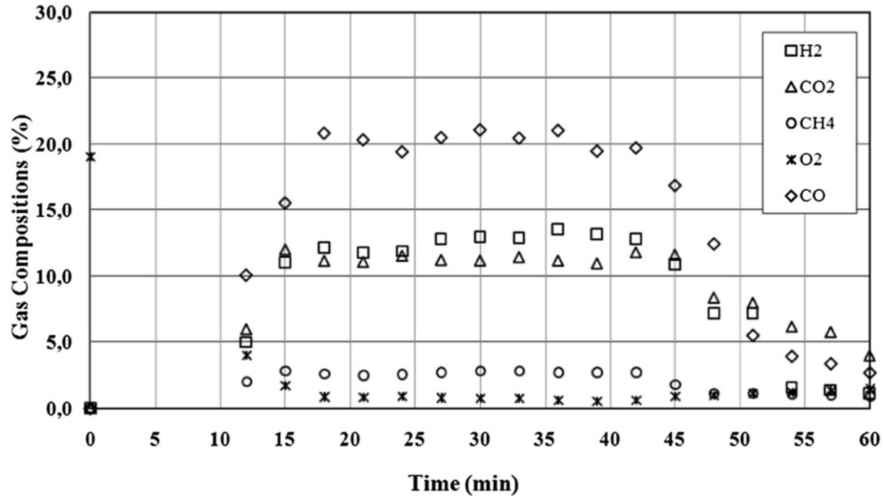

Fig. 9 – Gas compositions of wood chips experiments at ER = 0.35 during a batch operation.

Gasification experiments have been run smoothly without any major problems with wood chips and hazelnut shells. Neither gas leakage nor agglomeration problems have occurred in the gasifier. Morever no tar blockage is observed as long as the product gas is kept at temperatures which prevent tar condensation. Condensation of the tars in the product gas occurs in the gas cleaning section.

Fig. 5 shows the effect of the applied equivalence ratios (0.2–0.5) on the lower heating value of the product gas from wood chips during a whole batch operation. The average bench-scale process duration is approximately 1 h for a batch-load of 10 kg of wood chips. In the first half hour the lower heating value of the product gas increases to about 5 MJ/Nm^3 and gradually decreases to less then 1 MJ/Nm^3 in the next half hour. The effect of the equivalence ratios on the lower heating values of the product gas is more pronounced in the second part of the experiments.

Fig. 6 shows the highest lower heating values obtained at selected ER during batch operations with wood chips. The highest heating value is observed at 0.35 ER as 5.5 MJ/Nm^3. The increase of the ER above 0.35 decreases the gas product heating value enhancing further oxidation. The decrease of the ER below 0.35 on the other hand also results in lower heating values since its conditions support pyrolysis rather than gasification.

Fig. 7 presents the CO, CO_2, CH_4, H_2, O_2 contents of the product gases associated with the highest heating values. Carbon monoxide is the major combustible component with a percentage of 20–24. Hydrogen content is about 12–13 percent. Methane is around 3 to 4 percent. Carbon dioxide content is about 11–14 percent. Oxygen content is less than 1 percent. Among all of these constituents primarily CO is affected by the ER. The equivalence ratios at 0.25 to 0.4 appear to give acceptable product gas composition. The equivalence

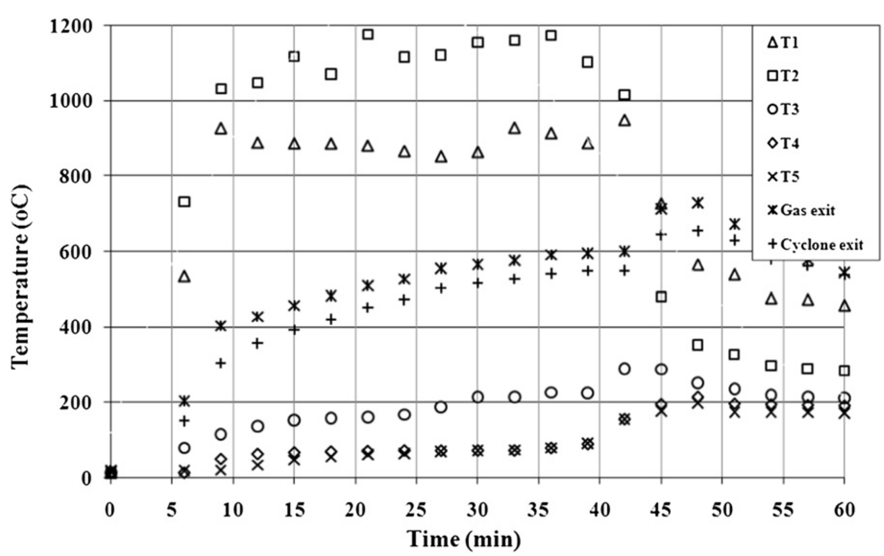

Fig. 10 – Temperature distributions along the gasifier during wood chips experiments at ER = 0.35.

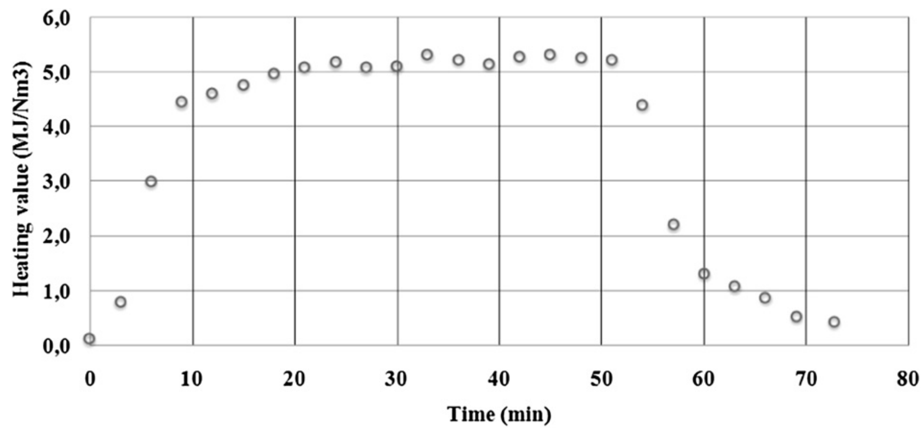

Fig. 11 – Heating values of hazelnut shell experiments at ER = 0.35 during a batch operation.

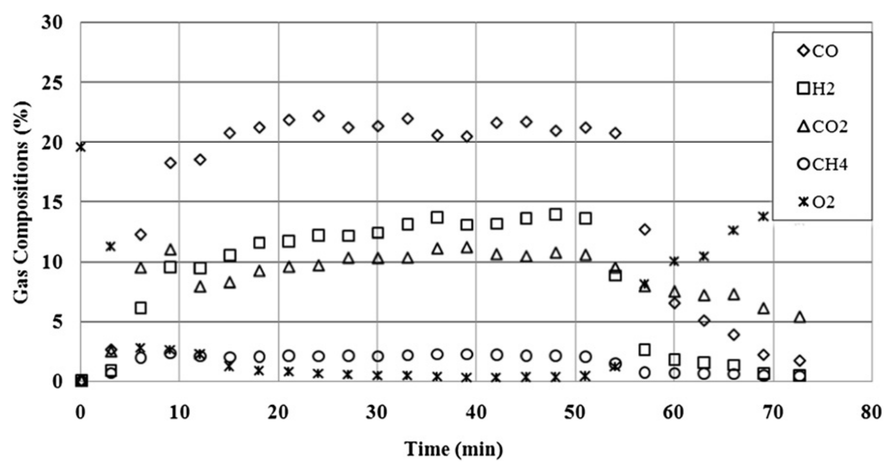

Fig. 12 – Gas compositions of hazelnut shell experiments at ER = 0.35 during a batch operation.

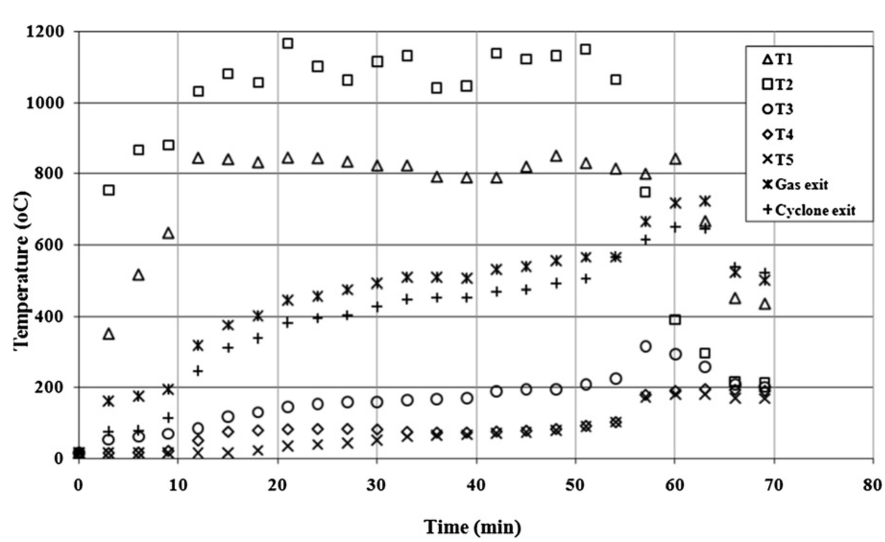

Fig. 13 – Temperature distributions along the gasifier during hazelnut shell experiments at ER = 0.35.

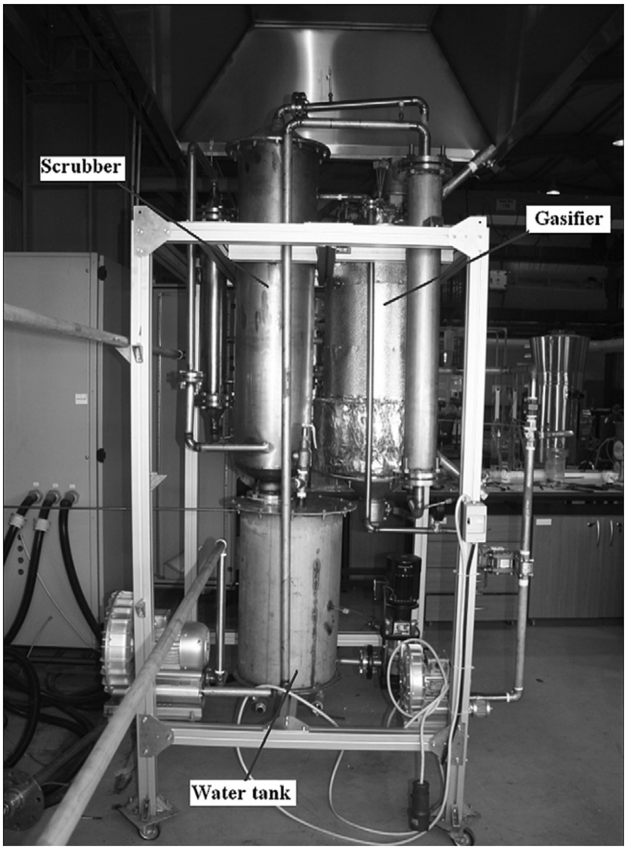

Fig. 14 – Modified gasifier.

ratio at 0.35 which yields the highest heating values is selected for detailed investigation.

Figs. 8 and 9 present the change of the heating values and the composition of the product gas at 0.35 ER during a full batch experiment. Fig. 10 shows the temperature distribution along the fixed bed gasifier during the before mentioned batch operation. The combustion zone temperature reaches 1000 °C in less than 10 min and stays below 1200 °C for about half an hour. At the same time the throat temperature is about 900 °C and the maximum gas exit temperature is read as 600 °C. The drying and pyrolysis zone temperatures are inline with the expectations.

Similar to wood chips, the preferred equivalence ratio range of hazelnut shells is 0.25–0.4 considering the product gas heating value. The results presented here for fixed bed gasification of hazelnut shells refer to the ER at 0.35 so that they can be compared with the wood chips results at ER = 0.35. Heating values, gas compositions and temperature distributions obtained during experiments with hazelnut shells at ER = 0.35 are presented in Figs. 11, 12 and 13, respectively.

Heating values above 4 MJ/Nm^3 are achieved in less than 10 min with hazelnut shells and similar quality gas is obtained for about 45 min (Figs. 11 and 12). With wood chips, 15 min are required to reach 4 MJ/Nm^3 and the delivery of this quality gas is limited to 30 min. These results are also reflected in the product gas compositions (Figs. 9 and 12). Temperature profiles of wood chips and hazelnut shells are quite similar except the fact that the latter show a longer lasting plateau (Figs. 10 and 13). The higher fixed carbon content of the hazelnut shells appears to support the delivery of high heating value gas for a longer time frame. The earlier on-set of high calorific value gas production with hazelnut shells is due to several factors. The shape and size of hazelnut shells are more homogeneous than wood chips which enable better gas solid contacts and enhance gasification reactions. Moreover thermal analyses have revealed that the low temperature volatile matter reactivity of hazelnut shells is more pronounced than with wood chips which may partially explain the earlier on-set high heating value gas production [21]. The slightly higher temperatures observed for wood chips in the pyrolysis and oxidation zones are supported by the relatively higher CO_2 contents of the wood chips based product gases indicating the presence of exothermic reactions along with endothermic ones.

4. Concluding remarks

The obtained heating values are acceptable. The ER resulting in the highest heating value product gas has been found as 0.35 for both biomass species investigated in this study. However, it should be noted that this ER level may change depending on the downdraft gasifier system design and the thermophysical and chemical biomass properties.

No operational problems such as tar blockage, agglomeration, process break down are observed with wood chips and hazelnut shells. Tar levels have not been quantitatively determined. However, it is semi-quantitatively observed that hazelnut shell gasification has produced more tar than wood chips gasification in spite of the higher volatile content of the former. Throated downdraft gasifiers appear as a suitable alternative for biomass gasification. Batch operation results can be easily adapted for continuous operation. Fig. 14 shows the gasifier used in the experiments modified for continuous operations in the future.

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